Electric Propulsion Orbital Platform

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ABSTRACT

This paper describes the status of the Electric Propulsion Orbital Platform (EPOP), the primary objective of which is to provide an instrumented platform for testing electric propulsion devices in space. It is anticipated that the first flight, EPOP-1, will take place on the Shuttle-deployed Wake Shield Facility in 1996, and will be designed around a modified version of a commercial 1.8 kW hydrazine arcjet system, to be operated on gaseous hydrogen propellant. Specific subsystems are described, including the arcjet system, the propellant and power systems, and the diagnostics systems.

INTRODUCTION

In January of 1992, a feasibility study was completed for the test of a 1.8 kW hydrazine arcjet system on the Wake Shield Facility [1]. This flight, EPOP-1, was envisioned as the first flight of the Electric Propulsion Orbital Platform (EPOP). EPOP is conceived as a space platform upon which NASA and U.S. industry can perform necessary space demonstrations of electric propulsion devices. As is well known, electric propulsion offers specific impulses which are significantly higher than those which can be obtained with conventional chemical systems. For example, the propellant exit velocity from arcjets is typically 50% larger than can be achieved by traditional chemical systems.

While the basic concept of the EPOP program has remained the same, significant changes have occurred. McDonnell-Douglas Space Systems Company has joined the EPOP-1 consortium, and will assume the technical lead. As before, Rocket Research Company and Boeing Defense & Space Group will be involved also, and the Space Vacuum Epitaxy Center (SVEC) will serve as the interface for integration of EPOP-1 on the Wake Shield Facility. Instead of hydrazine, gaseous hydrogen will be used as the propellant. This sets EPOP-1 apart as the only planned flight experiment involving a hydrogen arcjet, both in the U.S. and abroad. The immediate commercial motivation for the hydrogen arcjet flight experiment is to

develop a Solar Electric Orbital Transfer Vehicle (SEOTV). Such an SEOTV would serve to provide the McDonnell-Douglas Delta-2 launch vehicle with orbit-raising capability. A study by McDonnell-Douglas has shown that there is a substantial market for such an application, with an estimated 41 launches over the next twelve years.

EPOP will provide the following benefits to such commercialization of space: (1) A realistic demonstration of electric propulsion systems in the actual space environment; (2) The development of a national test facility that can be configured to user needs; and (3) The development of an infrastructure for the systematic advancement of electric propulsion technology.

In this regard, EPOP also enhances CSTAR's mission of reducing the cost of accessing space. Specifically, the knowledge gained from EPOP will contribute to improved thruster design and improved components for electric propulsion systems. Also, the EPOP program is laid out such that the knowledge and experience of each flight can be used for the further development of diagnostics for space applications of electric propulsion systems.

In this paper, we review the program concept and objectives for the EPOP program as a whole. Also, for the 1.8 kW hydrogen arcjet system demonstration of EPOP-1, we describe the top-level constraints imposed by the experiment carrier, and their implementation. The arcjet system, propellant system, the diagnostics systems, and mission aspects are also discussed. Previous descriptions of the EPOP program may be found elsewhere [2-4].

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PROGRAM CONCEPT AND OBJECTIVES

The objectives of the EPOP program are to develop a universal facility as a payload on several carriers for demonstrating electric propulsion devices in space; and, thereby, to develop a capability for characterizing the in-space operation of electric propulsion systems. In particular, the program will strive to increase the confidence of the satellite community in electric propulsion and promote commercial applications of electric propulsion systems by assembling data bases for the benefit of potential users, manufacturers, and integrators of electric propulsion systems.

The EPOP program will make maximum use of existing or planned NASA flight programs, such as Shuttle experiments, the Wake Shield Facility (WSF), COMET [5; p. 213], and Space Station Freedom (SSF). The program flight plan defined by the consortium is shown in Fig. 1, which strives for an initial gaseous hydrogen arcjet flight on WSF-03, to be followed by an ion thruster flight on WSF-04, a prototype orbit transfer vehicle mission based on a liquid hydrogen arcjet experiment on COMET, and, finally, a high-power, long-duration test of an arcjet or ion-thruster system on SSF. In addition to the demonstration of the electric propulsion systems themselves, EPOP enables the development and demonstration of specific subsystems, such as solar arrays, batteries, power conditioners, and diagnostics instrumentation.

This paper describes the first of these flight experiments, EPOP-1, a gaseous hydrogen experiment on the Wake Shield Facility. Mission objectives that have been established for EPOP-1 are:

- To demonstrate a complete hydrogen arcjet propulsion system;

- To develop and demonstrate an in-space electric propulsion test capability;

- To determine whether significant variations exist between ground-based and space-based operation of this arcjet system, including: electromagnetic characteristics, effects on the spacecraft, plume characteristics, and other operating characteristics.

Below, we address the specific implementation of these objectives, assuming Wake Shield to be the EPOP-1 carrier.

RATIONALE FOR AN IN-SPACE TEST

Many of the performance characteristics of an electric propulsion system can be characterized in ground tests. Even so, there is an inherent advantage to performing a demonstration in the actual space environment. This advantage stems both from the general demonstration of a completely integrated propulsion system, and the specific demonstration of specific components of this system.

A primary element of EPOP-1 will be the demonstration of a complete hydrogen feed system. Thus EPOP-1 will serve to reduce the risk of using new feed system components on a more expensive spacecraft. Also, as a result, critical components of the feed system will have already been tested before they are to be incorporated into a complete cryogenic storage system.

Another critical aspect of the flight experiment will be operation of the arcjet system itself. Specifically, ground tests have suggested that the operating voltage of the arcjet may be higher for the lower vacuum levels in the space test. This effect needs to be quantified so that the power conditioning unit can be designed accordingly.

Finally, since the arcjet is an electrothermal device, there is a question about the compatibility of the electromagnetic characteristics of the system with those of the spacecraft. EPOP-1 will attempt to address this compatibility issue. We anticipate that the space demonstration will prove to commercial users that hydrogen arcjet technology will be a highly desirable alternative to conventional chemical propulsion.
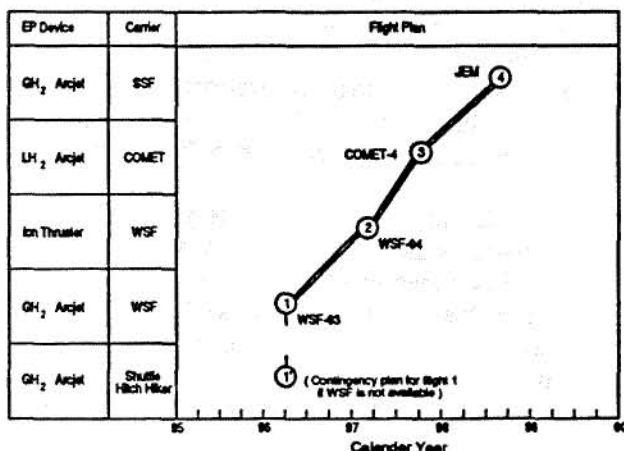
EP Device	Carrier	Flight Plan
GH₂ Arcjet	SSF	
LH₂ Arcjet	COMET	
Ion Thruster	WSF	
GH₂ Arcjet	WSF	
GH₂ Arcjet	Shuttle Hitch Hiker	

Fig. 1: *Program plan for first four EPOP flights.*

ARCJET SYSTEM

The decision to fly a 1.8 kW gaseous hydrogen arcjet experiment on EPOP-1 was based on maturity of the technology; specific interests on the part of the industrial consortium members; anticipated cost and funding figures; and consideration of other electric propulsion flight programs. Missions that will ultimately utilize hydrogen arcjets, for instance orbit transfer missions, will use arcjets that will require input powers of up to 30 kW. These higher power arcjets have been demonstrated in ground-testing to perform at specific impulses of up to 1500 s, at efficiencies of up to 40 percent [6].

However, a number of optimization and technical issues remain. These include performance optimization, establishment of the optimum voltage-current characteristic and mass flowrate for operation in a low-vacuum environment, heat dissipation, and electrode lifetime. We believe that operation of a lower power arcjet will allow some of these technical issues to be addressed along with a demonstration of a complete gaseous hydrogen arcjet.

It is intended to fly, on EPOP-1, a modified version of the 1.8 kW hydrazine arcjet system that has been developed at Rocket Research Company under a NASA Lewis Research Center grant [7]. A flight qualified version of this system [8] has been built by Rocket Research Company (see Fig. 2) for AT&T's Telstar 4 satellite, to be launched in 1993. This RRC 1.8 kW hydrazine arcjet (model MR 508) has a demonstrated Isp in excess of 500 s, and achieves a propellant savings of 200 kg over traditional chemical thrusters for a typical geosynchronous

communication satellite. This mass savings is exclusive of further mass savings in other areas, such as propellant tanks, support structure and launch vehicle.

The three components of the envisioned arcjet system include the arcjet thruster, the power cable, and the power conditioning unit (PCU). The latter may need to reconfigured for the higher operating voltage for hydrogen. The hydrazine arcjet, shown in Fig. 2, would be stripped of the catalyst bed, gas generator, valve heater, propellant valve, and fluid resistor. This hardware is used when hydrazine is the propellant to decompose and control the flow of the liquid propellant. Otherwise, it is not anticipated that significant modifications will be required to the design. Total mass of the system should be less than 6 kg.

Thermal considerations regarding integration of the arcjet system with the Wake Shield would center primarily around the PCU, which rejects less than 10 percent of the input power, or typically 160 to 165 W, to the spacecraft mounting interface. By contrast, typical heat rejection to the spacecraft from the arcjet body itself is less than 5 W, because most excess energy is radiated away from the nozzle tip, which is sprayed with a high emissivity coating.

In addition to actively conditioning the power to the arcjet, the PCU contains electrical interfaces to the data acquisition and control subsystem, the power supply, and the arcjet thruster. Also, the PCU is programmed to refire automatically in the case of misfirings of the arc. Once the arc is established, the PCU maintains constant power output (rather than constant voltage or constant current) to the arcjet.

PROPELLANT SYSTEM

EPOP-1 will store and deliver gaseous hydrogen to the arcjet. A schematic of the proposed propellant system is shown in Fig. 3. Gaseous hydrogen, stored at a maximum pressure of 1900 psia, will be supplied to the system through a pyrotechnic valve that will be opened at the beginning of the experiment. A 10 micron filter will be used to insure the gas is devoid of particles, and a pressure regulator will be used to lower the pressure from tank pressure to 15 psia. This low pressure was chosen to simulate the pressure that would be present if a cryogenic storage system were used — the storage method an actual transfer vehicle would use for reduced storage tank mass and volume. A compressor will be used to increase the line pressure to ~100 psia, the pressure required by the arcjet, with the actual pressure being regulated by a pressure regulator near the arcjet. The operation of this
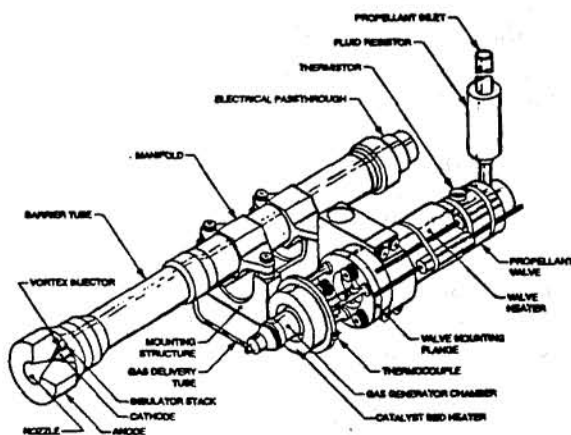

Fig. 2: *Schematic of a 1.8 kW arcjet, which is to be modified for EPOP-1. The hardware from the catalyst bed to the fluid resistor (foreground) will be removed.*
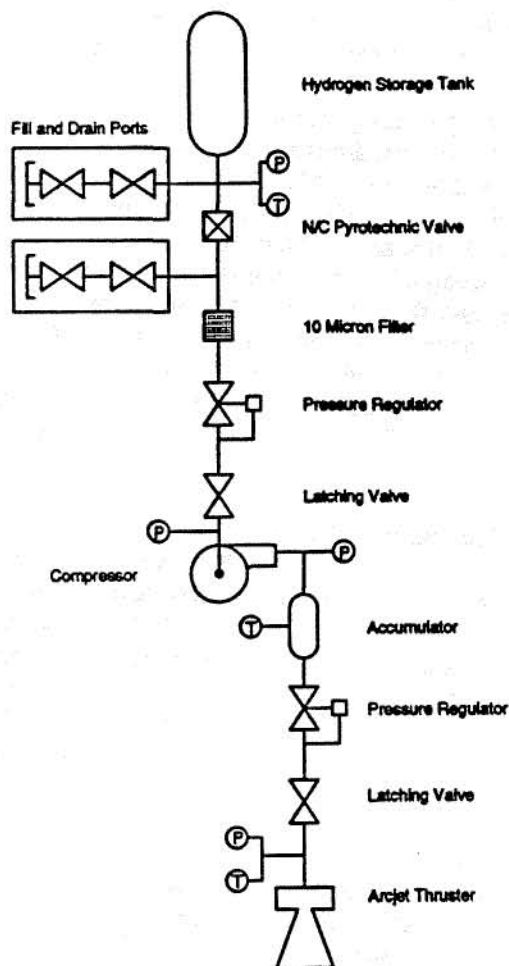
Fig. 3: *Schematic of the gaseous hydrogen propellant system for EPOP-1.*

flow control in a low-gravity environment is an important objective of demonstrating the operation of a complete hydrogen arcjet system. Temperature and pressure sensors are employed to help determine flowrates into the arcjet. Thus the actual flowrate will be calculated based on calibration measurements made before the flight.

EPOP-1 CARRIER

The Wake Shield Facility, being developed by the Space Vacuum Epitaxy Center (SVEC) at the University of Houston [5; p. 161], has been baselined as the carrier for EPOP. The primary aim of the WSF program is to utilize the vacuum environment of low Earth orbit (LEO) for materials processing in an ultra-clean environment; specifically, for epitaxial film growth experiments.

As shown in Fig. 4, the WSF is a circular stainless steel disk, 3.7 m in diameter. It is released from the

Table I: *Top-level constraints for EPOP-1.*

Constraint	Value
Maximum experiment mass	350 kg (770 lbm)
EPOP experiment time	24 hrs
Arcjet operation time	150 min. (cum.)
Peak power requirement	2 kW
WSF power available	< 500 W
Environmental constraints	1) Ultra-High vacuum 2) Shuttle constraints
Safety	Meet shuttle specs.
Telemetry	16 kbps Telemetry 64 kbps Video
Schedule	Launch June 96, WSF-03

Shuttle by the remote manipulator system (RMS) such that the axis normal to the surface is orientated along its orbital flight path. The EPOP experiment will be mounted (see Fig. 4), along with WSF's avionics, batteries, grapple fixture, and attitude control system on the ram side. Telemetry and control of WSF will be through an S-band RF link with the Shuttle. This link also allows for transmission of compressed video data. An obvious advantage of using WSF as the carrier for EPOP is the availability of these data links.

The use of WSF imposes several constraints on the EPOP experiment, specifically with regard to experiment time, experiment mass, available power, and telemetry. These are summarized in Table I. The goals and mission schedule for WSF necessitate that any arcjet firings be conducted after completion of all crystal growth experiments, leaving a period of about 24 hours until retrieval of the WSF by the Shuttle.

Insufficient power levels are available from WSF for a 1.8 kW experiment, so that EPOP must carry its own batteries. Due to a total mass limitation of 350 kg, the maximum net firing time of the arcjet system becomes limited to about 150 minutes. While this time is long enough to benchmark general performance of the arcjet system, it is too short to perform contamination studies.

DIAGNOSTICS SYSTEMS

To monitor the operation of the arcjet, and to enable a comparison between space- and ground-based operation, a number of diagnostics systems are under consideration for EPOP-1. These include systems that are EPOP-
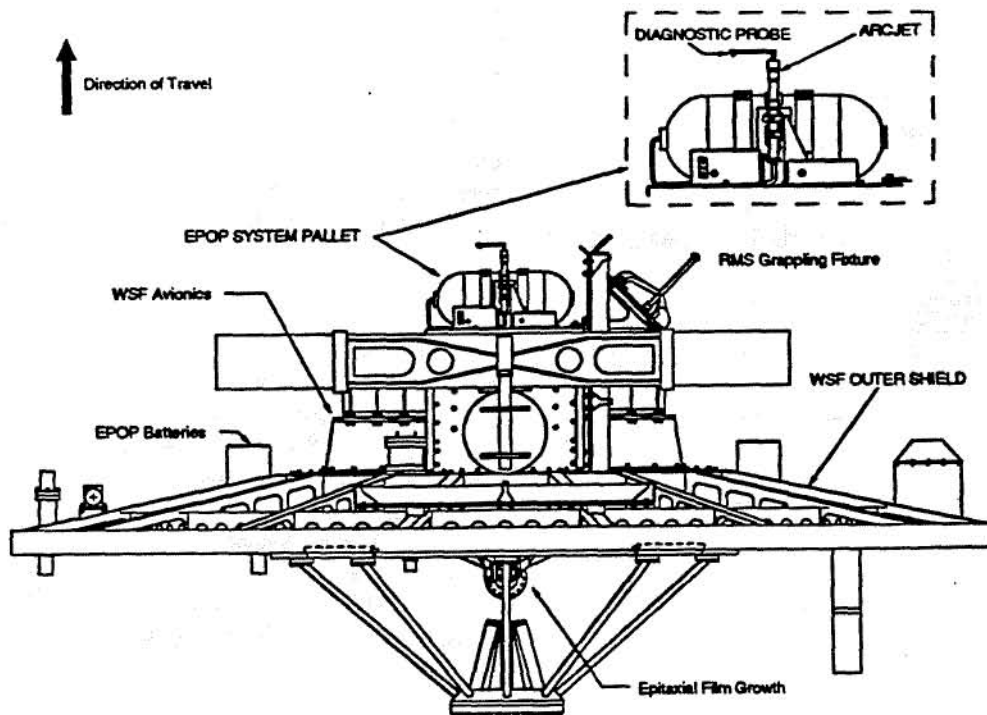
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Fig. 4: *Schematic of the Wake Shield Facility and the EPOP-1 experiment package.*

specific, as well as systems that are available from Wake Shield and the Shuttle. Systems from the first category are shown schematically in Fig. 5. These are:

(1) Electronics to measure output voltage and output current from the PCU to the arcjet, during steady-state operation as well as during the initial transient when the arc is initiated. In particular, the arc voltage is a sensitive indicator of arcjet performance. For example, it reflects fluctuations in propellant flow rate, and there is indication that the arc voltage for a given current and flowrate may be higher than for operation in a terrestrial vacuum chamber;

(2) Electronics to measure battery voltage and input current to the PCU. These measurements would serve primarily to allow for an unambiguous diagnosis of any unexpected arcjet behavior;

(3) Pressure and temperature transducers at several locations in the propellant feed system, to allow for calculation of the propellent mass flow of the thruster;

(4) Thermocouples and thermistors to measure temperatures at various points on the arcjet and the PCU. These measurements would be performed, for example, to estimate the radiative heat loss from the thruster, and to determine if heat losses from the PCU are dissipated adequately into the WSF structure;

(5) A camera and filter wheel assembly to obtain video data of the arcjet plume at different wavelengths. Video data can be used to analyze the stability of the plume, as well as to perform estimates of its core temperature, namely by comparing narrowband images taken at the hydrogen balmer-alpha and balmer-beta spectral lines, at 656.3 nm and 486.1 nm, respectively;

(6) A Langmuir probe to characterize the plasma properties of the arcjet plume. Specifically, measurements of the voltage-current characteristic of the probe would allow the calculation of electron density, electron temperature, plasma potential, and floating potential of the plume; if possible, a maneuverable probe will be used, so that radial sweeps of the plume can be performed.

In addition to these EPOP-specific diagnostics systems, a number of systems from the Wake Shield and the Shuttle would be available:

(7) Accelerometers, to determine the thrust of the arcjet system. Because the mass of the WSF is ~3000 kg,
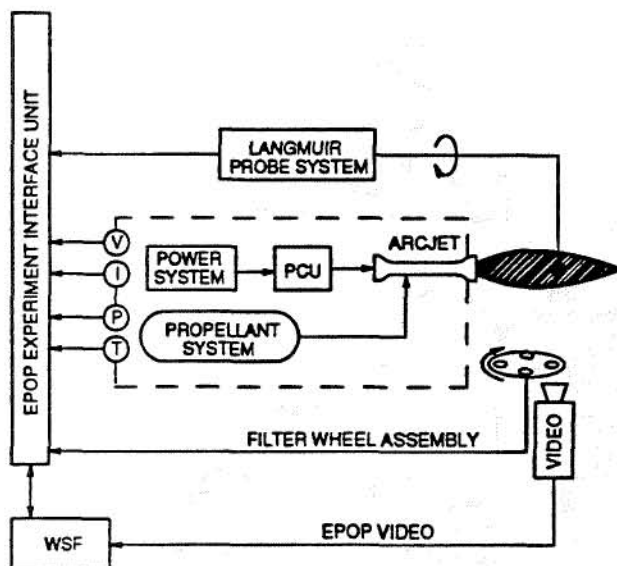
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Fig. 5: *Schematic of the EPOP-specific diagnostics systems.*

and arcjet thrust will be on the order of 0.2 N, the expected acceleration will be on the order of 7 μg. Thus the thrust measurement will only have a 15% accuracy. This in conjunction with the mass flow measurements above, would enable the calculation of a bracketed specific impulse that could serve to determine if measurements made on the ground are within this bracket. It should be noted that these acceleration measurements will be made independent of the EPOP demonstration.

(8) Use of the WSF communications link to perform additional electromagnetic interference characterization. This would be performed by error checking and noise analysis on the standard communication channel employed by WSF during firing of the arcjet system. Increased noise levels would constitute proof for electromagnetic characteristics at the frequency of the communication band (S-band). However, even a null result could be used to set upper limits on any noise from the arcjet system;

(9) If available, Phillips Laboratories' CHAWS plasma diagnostics package. In particular, coordination with this experiment would allow additional plasma characterization on both the ram and wake sides of the spacecraft, away from the arcjet thruster.

Finally, if Shuttle safety consideration would allow for thruster firings immediately prior to or during retrieval of the Wake Shield by the Shuttle's RMS, plume photography and video of the arcjet plume would be possible from the orbiter bay. One important diagnostic, namely characterization of contamination of spacecraft

surfaces as a result of arcjet operation, has been deemed too difficult, because of the relatively short operating time of the experiment.

Final selection of diagnostics subsystems and components for EPOP-1 will depend on funding and further analysis. It may not be practical to implement both types of electromagnetic characteristics diagnostics.

EPOP CONSORTIUM

A responsibility matrix for providing certain tasks for EPOP-1 is given in Table II. The table presents a general outline of responsibilities over the 5 year project. Although CSTAR is listed as having the lead in the EPOP program, technical and management decisions are made with complete consensus of the partners: McDonnell-Douglas Space Systems Company (MDC); Rocket Research Company (RRC); and Boeing Defense & Space Group (BD&SG). CSTAR has also taken the lead in developing and implementing the diagnostics to be used on EPOP.

McDonnell Douglas Space Systems Company will be the systems integrator for EPOP and will be the responsible partner for the areas that will support this role. They will also take the lead for the propellant and power supply subsystems, using their experience in this area.

Rocket Research Company will be responsible for production of the arcjet system. The arcjet system consists of three major subsystems: the arcjet thruster, the PCU and the triaxial power cable assembly connecting the

Table II: *Responsibility matrix for EPOP-1.*

	CSTAR	MDC	BD&SG	RRC	SVEC
Program Management	✓				
Diagnostics	✓				
System Engineering and Integration		✓			
Flight Operations		✓			
Power Supply		✓			
Propellant Subs.		✓			
Exp't Control & Data Acquisition			✓		
Arcjet and PCU				✓	
WSF Support and Modifications					✓

arcjet and PCU. The arcjet thruster is manufactured at RRC, while the PCU is manufactured at RRC's sister company Pacific Electro Dynamics, also located in Redmond, Washington. The power cable assembly is manufactured by Reynolds Industries, located in Los Angeles, California. Rocket Research Company is the arcjet system integrator, and performs project management and all integration and subsystem-level testing for the arcjet.

Boeing Defense & Space Group will be responsible for the experiment control and data acquisition subsystem. Finally, the Space Vacuum Epitaxy Center (SVEC) will be responsible for integration of the EPOP package on the Wake Shield Facility.

SUMMARY

We have explored the possibility of promoting the commercial use of electric propulsion systems in the U.S., namely by providing a flexible flight-testing capability for electric propulsion systems that would be funded jointly by NASA's Office of Commercial Programs and industry. In particular, we have performed a feasibility study for the flight of a 1.8 kW hydrogen arcjet experiment — EPOP-1 — aboard the Wake Shield Facility, a Shuttle-deployed free-flyer. At this point, it is envisioned that EPOP-1 will be manifested for a 1996 launch date.

Maximum cumulative thruster firing time for the experiment will be 2.5 hours. During this time, operating characteristics of the arcjet system will be monitored, including thrust, electrical efficiency, specific impulse, plasma properties of the plume, arcjet and plume temperatures, radio-frequency noise, and interference with spacecraft communications. Because of the small amount of hydrogen required, a simple gaseous storage system can be used. EPOP will draw supplemental power from the WSF bus, but primary power will be provided by a dedicated battery system. Thus, experiment time is limited by the maximum battery mass.

Responsibilities for the EPOP-1 experiment will be shared between CSTAR, which is a NASA-OCP-sponsored Center for the Commercial Development of Space, and industrial partners. At present, these partners are McDonnell Douglas Space Systems Company, Rocket Research Company, and Boeing Defense & Space Group. Also, as the responsible organization for the Wake Shield Facility, SVEC, another CCDS, will be involved.

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